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A Revised Lithostratigraphic Framework for the Southern Yucca Mountain Area, Nye County, Nevada

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Abstract *– An informal, revised lithostratigraphic framework for the southern Yucca Mountain area, Nevada has been developed to accommodate new information derived from subsurface investigations of the Nye County Early Warning Drilling Program. Lithologies penetrated by recently drilled boreholes at locations between Stagecoach Road and Highway 95 in southern Nye County include Quaternary and Pliocene alluvium and alluvial breccia, Miocene pyroclastic flow deposits and intercalated lacustrine siltstone and claystone sequences, early Miocene to Oligocene pre-volcanic sedimentary rocks, and Paleozoic strata. Of the 37 boreholes currently drilled, 21 boreholes have sufficient depth, spatial distribution, or traceable pyroclastic flow, pyroclastic fall, and reworked tuff deposits to aid in the lateral correlation of lithostrata. Medial and distal parts of regional pyroclastic flow deposits of Miocene age can be correlated with the Timber Mountain, Paintbrush, Crater Flat, and Tram Ridge Groups. Rocks intercalated between these regional pyroclastic flow deposits are substantially thicker than in the central part of Yucca Mountain, particularly near the downthrown side of major faults and along the southern extent of exposures at Yucca Mountain.*

I. INTRODUCTION

Geohydrologic investigations have been conducted since 1999 at known paleodischarge sites and along suspected hydrologic-flow and transport pathways in southern Nye County, Nevada, through the Nye County Early Warning Drilling Program (NCEWDP), funded by the U. S. Department of Energy (DOE).[1] Currently (2005), within an area of almost 400 square kilometers (km^2) that extends roughly from Stagecoach Road (southern end of Busted Butte) southward to U.S. Highway 95 within the southern Yucca Mountain and northern Amargosa Valley areas (fig. 1), a total of 37 boreholes have been drilled to depths ranging from 16.2 meters (m) to 937.3 m (fig. 2). On behalf of the DOE, the U. S. Geological Survey (USGS) continues to provide an independent interpretation of the lithostratigraphic framework of this area, based principally on examination of subsurface rock samples, collected jointly by representatives of the Nye County Nuclear Waste Repository Project Office (NWRPO) and DOE's Sample Management Facility.

Key to understanding the lithostratigraphic framework within the study area is the identification and correlation of medial and distal parts of regional pyroclastic flow deposits as well as lithologically and geochemically distinctive and laterally continuous pyroclastic fall layers and (or) intervals of volcaniclastic rock that extend southward from a more continuous volcanic succession beneath northern and central parts of Yucca Mountain (fig. 1). This paper summarizes a revised lithostratigraphic framework based on the current understanding of detailed subsurface lithostratigraphy within the study area with special emphasis on distribution of Miocene volcanic rocks.

II. GEOLOGIC SETTING OF NORTHERN AND CENTRAL YUCCA MOUNTAIN

Yucca Mountain consists of a 1- to 3-km-thick sequence of 11- to 14-million-year-old (m.y.-old) Miocene volcanic rocks, most of which are rhyolitic pyroclastic flow deposits that issued from source areas within the Timber Mountain caldera complex about 8 kilometers to the north.[2] These pyroclastic flow deposits, some of which reach several hundred meters in thickness, commonly are separated by thin (less than a few tens of meters in thickness) beds of volcaniclastic rocks that are composed chiefly of intercalated pyroclastic fall deposits and reworked tuff and commonly referred to as bedded tuffs. Most major pyroclastic flow deposits in this area decrease in thickness southward away from their source areas. The Miocene volcanic sequence rests on a several-kilometer-thick sequence of 600 to 300 m.y.-old Late Proterozoic and Paleozoic rocks that chiefly include rock types of limestone, dolomite, shale, argillite, and quartzite.[3]

III. METHODOLOGY

Subsurface lithostratigraphic interpretations by the USGS are based primarily on microscopic examination of drill-cuttings samples, laboratory analysis of selected specimens of drill-cutting samples, and review of available geophysical-log characteristics. Fundamental lithologic properties, such as rock type, degree of welding or induration, alteration characteristics, and geophysical-log characteristics, were compiled for boreholes that either reached a total depth greater than 185 m or penetrated pyroclastic flow deposits (fig. 2).

In concert with the lithostratigraphic compilations, a dual approach was used to corroborate the identity of pyroclastic flow and pyroclastic fall deposits, and in part, reworked tuffs. Both petrographic and trace-element analyses were performed on selected sets of drill-cutting specimens to determine percentages of essential mineral components and content of the relatively immobile trace elements zirconium (Zr), titanium (Ti), and barium (Ba). The petrographic analyses included estimates of quartz, alkali feldspar, plagioclase, and mafic phenocrysts as well as other diagnostic accessory phenocrysts such as sphene. The trace-element analyses, consisting of X-ray fluorescence (XRF) analyses of whole-rock samples of key reference sections[4], outcrop samples, and selected samples of core from boreholes within the central part of Yucca Mountain, provided diagnostic trace-element concentrations to aid in rapidly and reliably confirming the identity of many volcanic rock units.

Downhole geophysical data, which typically include density, moisture, acoustic, resistivity, gamma-ray, neutron, temperature, and caliper logs, were obtained in almost all boreholes greater than 185 m in depth; however, we conclude that only a few data sets provided reliable information for lithologic identification and correlation purposes. For example, downhole gravimetric measurements, obtained only in NC-EWDP-22SA and NC-EWDP-19D1, provided reliable density variability within thick Quaternary and Pliocene alluvium and Miocene tuff deposits. Resistivity and gamma-ray logging also provided corroborative information for confirming lithologic variations within alluvial sections and between volcaniclastic sequences and pyroclastic flow deposits. Although rarely of good quality due to poor visibility below the water table, which ranges from about 100 to 200 m below the ground surface throughout much of the study area, digital borehole optical televiewer logs proved to be one of the more important downhole logs for obtaining ancillary information such as attitudes of bedding planes and fracture information.

IV. REVISED LITHOSTRATIGRAPHIC FRAMEWORK

One of the more important findings of the subsurface interpretations within the study area has been the existence of thick (tens to hundreds of meters) interbedded gravel, conglomerate, reworked tuff, pyroclastic fall deposits, and lacustrine siltstone and claystone sequences that occupy lithostratigraphic positions between the medial and distal parts of major pyroclastic flow deposits (Table I). In northern and central Yucca Mountain, these same intervals commonly contain thin (only a few tens of meters) interbedded pyroclastic fall deposits and reworked tuff. Of the 37 currently drilled boreholes, 14 holes encountered pyroclastic flow and pyroclastic fall deposits, and (or) reworked volcaniclastic deposits, allowing their correlation with parts of the Timber Mountain, Paintbrush, Crater Flat, and Tram Ridge Groups (Table I).

On the basis of rock-type assemblages, the post-Paleozoic lithostratigraphic framework can be divided into two distinctive depositional environments within the study area. They are an eastern Crater Flat-southern Yucca Mountain environment and a Fortymile Wash-northern Amargosa Valley environment.

IV.A. Eastern Crater Flat- Southern Yucca Mountain

The eastern Crater Flat-southern Yucca Mountain environment is characterized by thick, partially exposed, pyroclastic flow deposits of Miocene age. These tuffs are intercalated with sequences of interbedded reworked tuff, siltstone, and claystone deposits, which, in turn, are underlain by pre-volcanic lacustrine claystone and siltstone of early Miocene to Oligocene age.

A noteworthy transition zone, where some lithostratigraphic units vary substantially in thickness and (or) lithologic character, occurs in an area in the general vicinity of Stagecoach Road (fig. 1). For example, a lone exposure of tuff resting on the Topopah Spring Tuff was mapped in the vicinity of Stagecoach Road (fig. 1) and informally referred to by Potter and others as the "Younger volcanic rocks" unit.[5] This tuff also is mapped in the subsurface, where 21.3 m of the unit was found to overlie the Ammonia Tanks Tuff in borehole NC-EWDP-28P. In borehole NC-EWDP-13P, 12.2 m of this unit directly underlies the 3.75 m.y.-old Younger Tertiary basalt of Crater Flat and overlies 55.6 m of pre-Younger volcanic rocks sedimentary rocks and 361.2 m of pre-Ammonia Tanks Tuff tuffaceous and sedimentary rocks. On the basis of petrographic analysis, distinctive trace-element concentrations, mineral separations, and attempts to determine its age, the Younger volcanic rocks unit has several unique characteristics. The unit contains (1) sphene (similar to the Ammonia Tanks Tuff) and (2) substantially higher concentrations of Ba than in underlying rocks of the Timber Mountain Group. An attempt to determine its age by the laser-fusion ^{39}Argon/^{40}Argon ($^{39}Ar/^{40}Ar$) dating method[2] of feldspar phenocrysts revealed distinctive age ranges of 11.4 to 11.5, and 11.6 to 11.7 million years (m.y), strongly indicating that the tuff contains substantial amounts of both the underlying Rainier Mesa and Ammonia Tanks Tuffs (R. J. Fleck, U.S. Geological Survey, written comm., 2005). However, a few feldspar phenocrysts yielded ages as young as 9.7 m.y. (R. J. Fleck, U.S. Geological Survey, written comm., 2005). Although of local areal extent, this tuff represents an important stratigraphic marker unit within the uppermost part of the volcanic section. South of Stagecoach Road, thickness variations of this unit indicate local accumulation along the downthrown side of the Stagecoach Road, Paintbrush Canyon, and Windy Wash faults (fig. 1). South of Stagecoach Road, the Younger volcanic rocks unit, when combined with the underlying pre-Younger volcanic rocks sedimentary rocks and rocks of the Timber Mountain Group reach a composite thickness of 246.2 m in borehole NC-EWDP-28P and 432.6 m in borehole NC-EWDP-13P (Table II).

The extensively exposed and regionally distributed Tiva Canyon and Topopah Spring Tuffs of the Paintbrush Group are thinner within the study area than in northern and central Yucca Mountain. The Tiva Canyon Tuff varies uniformly in thickness from about 19.1 m to 75.3 m within the study area. The Topopah Spring Tuff ranges in thickness from 237.7 m in borehole NC-EWDP-27P in the northern part of the study area to 27.4 m in borehole NC-EWDP-2DB near the southern part of the study area (fig. 1, Table II). Both tuffs, however, are conspicuously absent in borehole NC-EWDP-13P directly west of the Windy Wash fault and in borehole NC-EWDP-7SC in southern Crater Flat, where they are presumed to have been eroded. Their stratigraphic position is now occupied by tens to hundreds of meters of volcaniclastic sediments (dominantly gravels and reworked tuffs), interpreted as the Younger volcanic rocks unit, pre-Younger volcanic rocks sedimentary rocks, and rocks of the Timber Mountain Group (Tables I and II).

Stagecoach Road also appears to mark a transition within the Topopah Spring Tuff. Throughout much of the area north of Stagecoach Road, the crystal-rich member of the Topopah Spring Tuff is as pervasive as the underlying crystal-poor member. South of the Stagecoach Road, the crystal-rich member is not present except near the extreme southern terminus of outcrops of the Topopah Spring Tuff[11], directly north of borehole NC-EWDP-15D and at borehole NC-EWDP-29P (fig. 1).

Beneath northern and central Yucca Mountain, the Topopah Spring Tuff is underlain by only a few meters of pyroclastic fall and (or) reworked tuff layers.[3,7] However, south of Stagecoach Road, (fig. 1), particularly along the downthrown side of the Windy Wash, Stagecoach Road and Paintbrush Canyon faults, the Topopah Spring Tuff is underlain by hundreds of meters of intercalated pyroclastic fall deposits, reworked tuffs, and tuffaceous siltstone and sandstone. At the NC-EWDP-18P and NC-EWDP-28P borehole sites, 27.4 and 281.9 m, respectively, of intercalated crystal-poor ash-fall tuff deposits, intervals of crystal-poor reworked tuff, and deposits of siltstone occur directly below the Topopah Spring Tuff. The total thickness of these thick deposits remains unknown, as both boreholes were terminated within these interbedded Tertiary sedimentary sequences. An alternative hypothesis is that these thick lacustrine deposits underlying the Topopah Spring Tuff in borehole NC-EWDP-28P occupy a much lower stratigraphic position below the Tram Tuff.[12] Intrinsic to this hypothesis is the assumption that at places within the central part of the study area (near boreholes NC-EWDP-18P and NC-EWDP-28P), all of the pyroclastic flow deposits within the Crater Flat Group had been either completely eroded or were never deposited on high-standing pre-Crater Flat Group horsts. Intervals of reworked tuff within the Crater Flat and Tram Ridge Groups, however, characteristically contain very high concentrations of sanidine, plagioclase, and mafic phenocrysts. More than 150 parts per million (ppm) of Zr and 400 ppm of Ba are typically found in reworked tuffs below the Bullfrog Tuff of the Crater Flat Group. In marked contrast, tuffaceous sediments within and directly below the Paintbrush Group typically contain few phenocrysts, have Ba concentrations less than 200 ppm, and Zr concentrations less than 150 ppm. As noted previously, rocks of the Crater Flat Group in nearby boreholes NC-EWDP-16P and -24P are approximately 300 m thick. The absence of abundant intervals of crystal-rich tuff, the trace-element signatures of reworked tuff in boreholes NC-EWDP-18P and NC-EWDP-28P, and the existence of substantial thicknesses of rocks of the Crater Flat Group in surrounding boreholes all are evidence against this alternative stratigraphic interpretation.

Interpreted to thin substantially southeast of Busted Butte on the basis of surface exposures[5], the Wahmonie Formation occurs in two boreholes, separating rocks of Paintbrush and Crater Flat Groups. The Wahmonie Formation is currently known to occur in the subsurface as far west as borehole NC-EWDP-16P and as far to the southeast as borehole NC-EWDP-29P, where it is 25.6 m and more than 44.2 m thick, respectively. Although not mapped by Potter and others [5], the Wahmonie Formation, measuring 14.6 m[4], also crops out between the Prow Pass and Topopah Spring Tuffs as far southwest as the southernmost exposures of pyroclastic flow deposits at Yucca Mountain (fig. 1).

Rocks of the Crater Flat Group were found in drill holes NC-EWDP-2DB, -16P, -3D, -1DX, -27P, -24P, -13P, -7SC, and -15D. The most complete stratigraphic succession of rocks from the Crater Flat Group occurs in borehole NC-EWDP-16P, where the Prow Pass, Bullfrog, and Tram Tuffs are 112.8, 160.6, and 25.9 m thick, respectively.

To the southeast, between exposures of the volcanics in southern Yucca Mountain and the thick alluvial cover near Fortymile Wash, samples from borehole NC-EWDP-24P, reveal a nearly complete sequence of the Bullfrog, Tram, and Lithic Ridge Tuffs, separated by only a few meters of volcaniclastic rocks or lacustrine deposits. At this locality, the Bullfrog, Tram, and Lithic Ridge Tuffs are 149.4, 129.5, and 114.3 m thick, respectively. Directly north of the Highway 95 fault (fig.2), borehole NC-EWDP-3D contains 50.9, 129.5, and 41.8 m of the Tram Tuff, Lithic Ridge Tuff, and the underlying Rhyolite of Picture Rock, respectively. Unlike other localities within southern Yucca Mountain, these older tuffs are separated by as much as 232.6 m of interbedded reworked tuff, claystone, and siltstone of Miocene age. Judging from these subsurface thicknesses and their regional extent,[2,5] these tuffs within the Crater Flat Group and the Lithic Ridge Tuff persist as continuous layers throughout the study area.

IV.B. Fortymile Wash and Northern Amargosa Valley

The higher-energy alluvial environment of adjacent Fortymile Wash-northern Amargosa Valley is dominated by much thicker Quaternary and Pliocene alluvial-fan deposits, resting on a thinner cover of Miocene volcanic rocks, and underlain by pre-volcanic fluvial and lacustrine deposits, composed of gravels, claystone, siltstone, and limestone. Boreholes drilled near the main channel of Fortymile Wash (NC-EWDP-10SA and -22SA) indicate that more than 365.7 m of Quaternary and Pliocene alluvium are present, the base of which has not been confirmed by drilling. However, over a distance of 2.6 km, these alluvial deposits thin markedly near the western margin of the Fortymile Wash area to 121.9 m and 94.5 m in boreholes NC-EWDP-24P and -29P, respectively (fig. 1, Table II).

Important to hydrologic modeling of the geohydrology of the Fortymile Wash area, the location where welded tuff transitions into more porous alluvium near the water table remains unconfirmed. This interface probably occurs near the projection of an unnamed, down-to-the-northwest fault between boreholes NC-EWDP-10SA and -22SA (fig 1).

In the subsurface near Fortymile Wash, a distinctive and mappable lowermost alluvial unit that commonly forms a veneer directly above the Miocene volcanic rocks was recognized. This unit is monolithologic, containing small to large blocks of crystal-poor Tiva Canyon Tuff, many of which are coated with a matrix of light-brown crystal-rich reworked tuff. This unit, for the most part, is a sedimentary breccia; however, a thin basal subunit of unconsolidated to poorly consolidated conglomerate also has been recognized. This basal alluvial unit is herein informally referred to as Tertiary alluvial breccia (Tab; Tables I and II). Gravimetric measurements from borehole NC-EWDP-22SA indicate that this informal unit commonly has a high density (similar to tuff), ranging from 2.1 to 2.2 grams per cubic centimeter (g/cm^3). Although thickest near the main channel of Fortymile Wash, where it exceeds 133.5 m in borehole NC-EWDP-10SA and 45.7 m in borehole NC-EWDP-22SA, the alluvial unit also has been found directly above the Miocene volcanic rocks in boreholes NC-EWDP-16P, -27P, and -29P.

Currently (2005), the only two holes in the area drilled deep enough to penetrate a substantial part of the underlying Miocene volcanic rocks are boreholes NC-EWDP-19D1 and NC-EWDP-2DB, located on opposite sides of the Highway 95 fault (fig. 1) in the northern Amargosa Valley. Borehole NC-EWDP-19D1, located on the north side of the Highway 95 Fault, drilled through 134.1 m of a thick nonwelded pyroclastic flow deposit. The deposit is highly vesiculated, pumice-rich, zeolitic, and has a relatively uniform density of 1.9 g/cm^3, based on downhole gravimetric measurements. On the basis of low concentrations of Ti, Zr, and Ba, very few phenocrysts and, in particular, very few quartz phenocrysts, this unit is interpreted as the Topopah Spring Tuff. However, this deposit lacks the zonal variation in welding typically found in nearby outcrops and in NC-EWDP-2DB. In borehole NC-EWDP-2DB, where it is only 27.4 m thick, the Topopah Spring Tuff maintains its typical vertical zonal characteristics. The anomalous thickness and absence of typical zonal characteristics at the site of borehole NC-EWDP-19D1 is attributed to the accumulation of this tuff against a presumed buried fault scarp along the northern downthrown-side of the Highway 95 Fault (Fig. 1).

As the southernmost deep borehole, NC-EWDP-2DB defines the southernmost lithostratigraphic section. In this part of northern Amargosa Valley, the Miocene volcanic rocks are composed of (1) distal margin of the Topopah Spring Tuff, (2) pre-Topopah Spring Tuff tuffaceous and sedimentary rocks, (3) pre-Bullfrog Tuff tuffaceous and sedimentary rocks, (4) Tram Tuff, and (5) pre-Tram Tuff tuffaceous and sedimentary rocks, has been interpreted to underlie more than 280.7 m of unconsolidated Quaternary and Pliocene gravel and sand. Below the Miocene volcanic rocks, 486.2 m of intercalated gravel, sandstone, siltstone, claystone, and limestone is present (Tables I and II). The lowermost 86.9 m of this pre-volcanic section is dominated by quartzite-rich conglomerate and lacustrine silty limestone, which may be equivalent to Miocene to Oligocene rocks of Pavits Spring[10] and rocks of lower Rock Valley[5] (Table I). Below this prevolcanic section, 36.6 m of Paleozoic limestone and dolomite were drilled prior to reaching total depth.

V. CONCLUSIONS

Interpretations of the lithostratigraphy from boreholes of the NCEWDP have contributed substantially to the overall understanding of the distribution of rocks in eastern Crater Flat, southern Yucca Mountain, Fortymile Wash, and northern Amargosa areas. These findings indicate substantial differences in the lithostratigraphic framework between northern and central Yucca Mountain and this study area to the south. Most noteworthy are the thick intercalated sequences of Miocene lacustrine siltstone and claystone, previously thought to occupy only pre-volcanic stratigraphic positions near Yucca Mountain, which are now incorporated into the lithostratigraphic framework as mappable rock units, separating medial to distal parts of regional pyroclastic flow deposits of the Paintbrush, Crater Flat, and Tram Ridge Groups of Miocene age. Near the southern end of Yucca Mountain, these sedimentary sequences are much thicker than the intervening pyroclastic flow deposits and may affect the modeling of vertical zonation of hydrologic properties in these areas. The deposition of the thick pre-Younger volcanic rocks sedimentary rocks, pre-Ammonia Tanks Tuff tuffaceous and sedimentary rocks, and pre-Topopah Spring Tuff tuffaceous and sedimentary rocks are believed to be localized near downthrown sides of major faults.

These thick accumulations may result in abrupt lateral juxapositional characteristics of geohydrologic properties, where thick, poorly consolidated intervals of volcaniclastic rocks and (or) fine-grained, highly indurated siltstone and claystone occur adjacent to welded pyroclastic flow deposits.

Boreholes of the NCEWDP in southern Yucca Mountain also have led to a better understanding of the distribution of the Younger volcanic rocks unit and the Wahmonie Formation. These new lithostratigraphic findings in eastern Crater Flat, southern Yucca Mountain, Fortymile Wash, and northern Amargosa Valley areas continue to improve understanding of the lithostratigraphic framework for eventual incorporation into more accurate and realistic hydrogeologic framework models.

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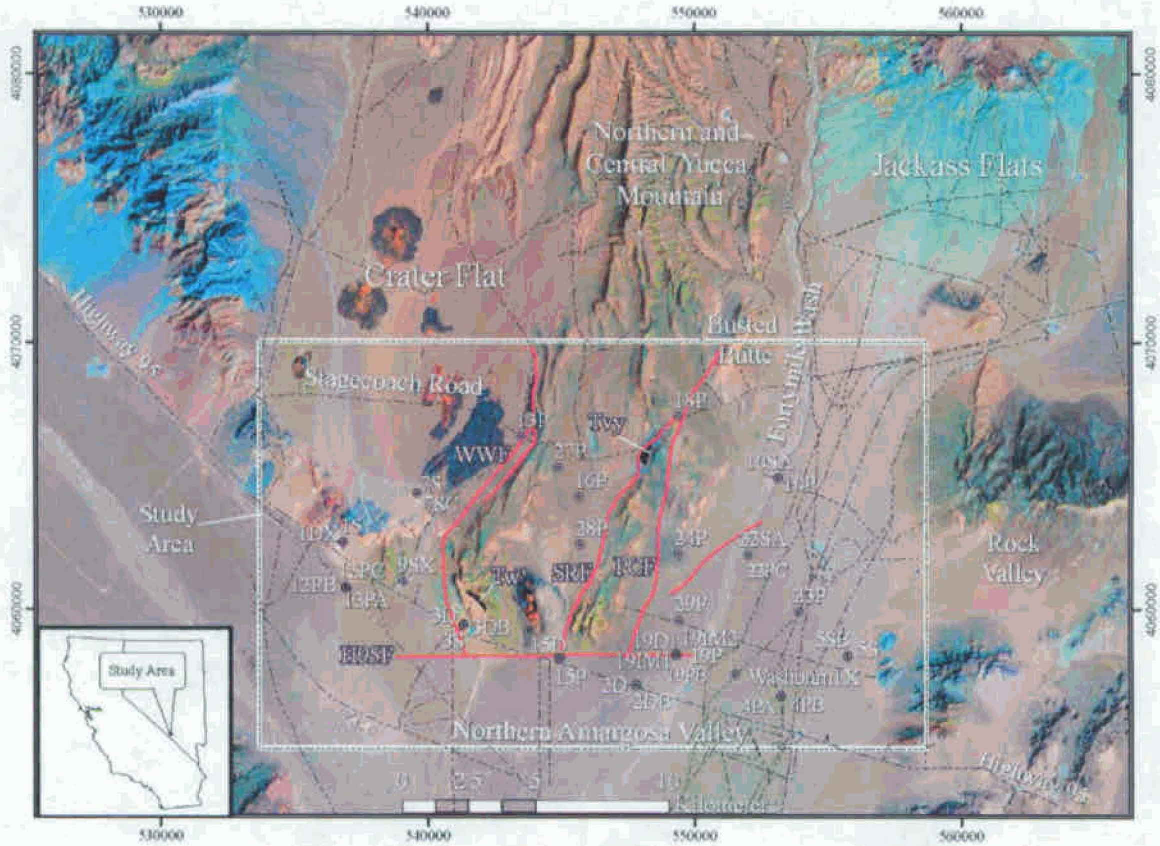

Figure 1. Color-composite map of Landsat-5 imagery (04-05-1996) of the Yucca Mountain area, Nye County, Nevada, showing the location of boreholes by borehole designation (see Table II) of the Nye County Early Warning Drilling Program completed between 1999 and 2005. All borehole designations have a prefix of NC-EWDP-. The outcrop, labeled Tvy, represents the lone exposure of the Younger volcanic rocks unit.[5] The outcrop, labeled Tw, represents an exposure of the Wahmonie Formation within the study area.[4] Selected inferred surface traces of down-to-the-west fault segments (shown in red) are: WWF, Windy Wash fault; SRF, Stagecoach Road fault; PCF, Paintbrush Canyon fault; and an unnamed northeast-trending fault crossing part of the Fortymile Wash area. Also shown in red is the inferred surface trace of the east-trending, down-to-the-north, strike-slip Highway 95 Fault (H95F; modified from Potter and others, 2002[5]). Dashed black lines represent selected primary, secondary, and unimproved roads. 10,000-m grid ticks based on Universal Transverse Mercator (UTM) coordinate system and North American datum (NAD) 27.

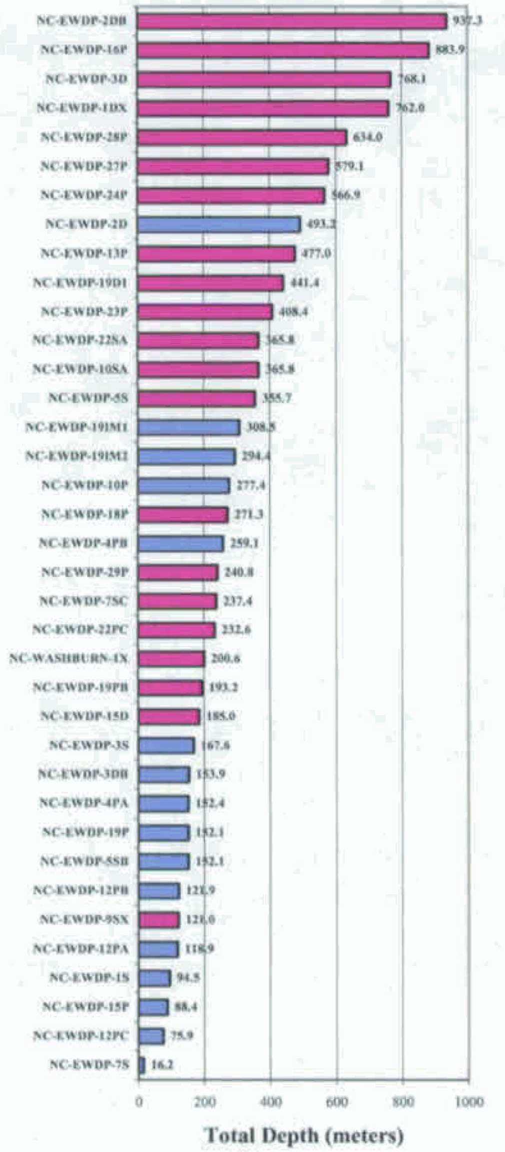

Figure 2. Distribution of total depths of holes drilled from 1999 to 2005 as part of the Nye County Early Warning Drilling Program (NCEWDP). Dark red bars represent NCEWDP boreholes used in this report.

TABLE I. Informal, revised lithostratigraphic framework for southern Yucca Mountain. Rock units that are underlined represent proposed additions or modifications to accommodate new lithostratigraphic information from boreholes of the Nye County Early Warning Drilling Program that were drilled between 1999 and 2005, in eastern Crater Flat, southern Yucca Mountain, Fortymile Wash, and northern Amargosa Valley, Nye County, Nevada.

LITHOSTRATIGRAPHIC UNIT	AGE (MILLIONS OF YEARS)[a]
	Quaternary and Pliocene
Quaternary and Pliocene alluvium (undifferentiated) (QTu)	
Younger Tertiary basalt of Crater Flat (Tby[5])	3.75[b]
Tertiary alluvial breccia (Tab)	
(includes sedimentary breccia and may include a basal conglomerate)	
	Miocene
Younger volcanic rocks-(Tvy[5])	9.7[c]
Pre-Younger volcanic rocks sedimentary rocks (Tvys)	
(includes poorly consolidated conglomerate and reworked tuff and minor lacustrine siltstone and claystone.)	
Timber Mountain Group	
Ammonia Tanks Tuff (Tma[5])	11.45
Pre-Ammonia Tanks Tuff tuffaceous and sedimentary rocks-(Tmas)	
(commonly includes gravel, conglomerate, and reworked tuff)	
Rainier Mesa Tuff-(Tmr[5])	11.6
Pre-Rainier Mesa Tuff Tuffaceous and sedimentary rocks (Tmrs)	
(No Pre-Rainier Mesa Tuff tuffaceous and sedimentary rocks have found between the Tmr and the underlying Tpc in any current (1999-2005) boreholes of the NCEWDP, however, thick deposits of reworked tuff occur in the subsurface directly north of the study area.)	
Paintbrush Group	
Tiva Canyon Tuff (Tpc[7])	12.7
Paintbrush Group bedded tuff (Tpbt[7])	
(commonly includes reworked tuff and pyroclastic fall deposits, may include Tpbt4, Tpbt3, and Tpbt2)[7]	
Topopah Spring Tuff (Tpt[7])	12.8
Crystal-rich Member (Tptr[7])	
Crystal-poor Member (Tptp[7])	
Pre-Topopah Spring Tuff tuffaceous and sedimentary rocks (Tpts)	
(includes Tpbt1[7], lacustrine siltstone and claystone and reworked and pyroclastic fall deposits)	
Calico Hills Formation (Tac[5])	12.9
Although the Calico Hills Formation was not found in any current (1999-2005) boreholes of the NCEWDP, it is included as part of the lithostratigraphy because of thin outcrops along the southern flank of Busted Butte within the study area.[8]	
Wahmonie Formation (Tw[5])	13.0
(commonly includes both pyroclastic flow and pyroclastic fall deposits)	
Crater Flat Group	
Prow Pass Tuff (Tcp[5])	
Pre-Prow Pass Tuff bedded tuff-(Tcpbt[5])	
Bullfrog Tuff-(Tcb[5])	13.25
Pre-Bullfrog Tuff tuffaceous and sedimentary rocks (Tcbts)	
(upper part is commonly dominated by crystal-rich reworked tuff; lower part is commonly dominated by lacustrine siltstone and claystone)	
Tram Tuff-(Tct[5])	
Pre-Tram Tuff tuffaceous and sedimentary rocks (Tcts)	
(commonly includes lacustrine siltstone and claystone and reworked tuff)	
Tram Ridge Group[8]	
Lithic Ridge Tuff (Trl[8])	14.0
Pre-Lithic Ridge Tuff tuffaceous and sedimentary rocks (Trls)	
(commonly includes lacustrine siltstone and claystone and reworked tuff)	
Rhyolite of Picture Rock (Trr[8])	
Pre-volcanic sedimentary rocks (Tge[9])	**Miocene to Oligocene**
(commonly includes lacustrine limestone, siltstone, claystone, and gravel; may include rocks of Pavits Spring[10] and possibly rocks of lower Rock Valley[5])	
Paleozoic rocks (undivided, Pz)	**Devonian and Silurian**

[a]Except where indicated, ages of units are from [2]; [b]Age of Younger Tertiary basalt of Crater Flat [6]; [c] age of youngest feldspar phenocrysts from Tvy (R. J. Fleck, U. S. Geological Survey, written communications, 2005).

Table II. Thickness (in meters) of traceable lithostratigraphic units found in 21 boreholes of the Nye County Early Warning Drilling Program between 1999 and 2005.

DH=abbreviated borehole designation (all holes include NC-EWDP- as a pre-fix); QTu=Quaternary and Pliocene alluvium (undifferentiated); Tab=Tertiary alluvial breccia; Tby=Younger Tertiary basalt of Crater Flat; Tvy=Younger volcanic rocks; Tvys=Pre-Younger volcanic rocks sedimentary rocks; Tma=Ammonia Tanks Tuff; Tmas=Pre-Ammonia Tanks Tuff tuffaceous and sedimentary rocks, Tmr=Rainier Mesa Tuff; Tpc=Tiva Canyon Tuff; Tpbt=Paintbrush Group bedded tuff; Tptr=crystal-rich Member of the Topopah Spring Tuff; Tptp=crystal-poor Member of the Topopah Spring Tuff; Tpts=Pre-Topopah Spring Tuff tuffaceous and sedimentary rocks; Tw=Wahmonie Formation (may include pyroclastic flow, pyroclastic fall, and reworked deposits); Tcp=Prow Pass Tuff; Tcpbt=Pre-Prow Pass Tuff bedded tuff; Tcb=Bullfrog Tuff; Tcbts=Pre-Bullfrog Tuff tuffaceous and sedimentary rocks; Tct=Tram Tuff; Tcts=Pre-Tram Tuff tuffaceous and sedimentary rocks; Trl=Lithic Ridge Tuff; Trls=Pre-Lithic Ridge Tuff tuffaceous and sedimentary rocks; Trr=Rhyolite of Picture Rock; Tge=Pre-volcanic sedimentary rocks; Pz=Paleozoic rocks (undivided). Leader (—) indicates unit not present; plus sign (+) indicates partial thickness because the base of unit was not encountered.

DH	QTu	Tab	Tby	Tvy	Tvys	Tma	Tmas	Tmr	Tpc	Tpbt	Tptr	Tptp	Tpts	Tw	Tcp	Tcpbt	Tcb	Tcbts	Tct	Tcts	Trl	Trls	Trr	Tge	Pz
2DB	280.7	—	—	—	—	—	—	—	—	—	—	27.4	18.3	—	—	—	—	25.6	15.2	47.2	—	—	—	486.2	36.6+
16P[a]	26.7	23.6	—	—	—	—	71.6	144.8	61.0	1.5	—	217.9	7.9	25.6	112.8	0.9	160.6	3.0	25.9+	—	—	—	—	—	—
3D	48.5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	59.7	50.9	232.6	129.5	7.0	41.8	198.1+	—
1DX	47.2	—	—	—	—	45.7	21.3	—	—	—	—	—	249.9	—	—	—	—	—	18.3	18.3	11.6	142.3	3.0	204.2+	—
28P	31.2	—	—	21.3	29.0	46.5	74.7	74.7	48.8	—	—	25.9[b]	281.9+	—	—	—	—	—	—	—	—	—	—	—	—
27P	47.2	10.7	—	—	—	—	3.0	—	48.8	13.7	—	237.7	50.3	—	125.0	1.5	41.1+	—	—	—	—	—	—	—	—
24P	121.9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	149.4	12.2	129.5	4.6	114.3	35.1+	—	—	—
13P	26.5	—	13.9	12.2	55.6	—	361.2[c]	—	—	—	—	—	—	—	—	—	7.6+	—	—	—	—	—	—	—	—
19D1	249.9	—	—	—	—	—	—	—	—	—	—	134.1	57.3+[d]	—	—	—	—	—	—	—	—	—	—	—	—
23P[e]	408.4+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
22SA	320.0	45.7+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
10SA	232.3	133.5+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5S	355.7+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
18P	13.7	—	—	—	—	—	—	—	64.0	6.1	—	160.0	27.4+	—	—	—	—	—	—	—	—	—	—	—	—
29P	94.5	2.3	—	—	—	—	—	—	19.1	8.2	28.3	41.8	2.4	44.2+	—	—	—	—	—	—	—	—	—	—	—
7SC	71.6	—	—	—	—	4.0	93.6	—	—	—	—	—	3.0	—	16.8	—	48.5+	—	—	—	—	—	—	—	—
1X	200.6+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
19PB	193.2+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
15D	88.4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	67.0	29.6+	—	—	—	—	—	—
22PC	140.2+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
9SX	45.7	—	—	—	—	—	—	—	75.3+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

[a]Severe hole deviation occurred in 16P and thicknesses are uncorrected; [b]thin (25.9 m) Tptp in 28P is attributed to a normal fault cutting out the upper part of the Topopah Spring Tuff; [c]thick Tmas in 13P may also include some Tvys, Pre-Rainier Mesa Tuff tuffaceous and sedimentary rocks (Tmrs), and Tpts; [d]lower part of Tpts in 19D1 may include older sediments;;. [e]lowermost 12.2 m in 23P encountered a dike or sill of crystal-rich, 10 m. y.-old basalt (unpublished age from R. J. Fleck, U.S Geological Survey, written communications, 2004).